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(71) Applicant(s)
Robert Bosch GmbH
(Incorporated in the Federal Republic of Germany)
Postfach 30 02 20, D-70442 Stuttgart 30, Federal Republic of Germany

(72) Inventor(s)
Volker Becker
Franz Laermer
Andrea Schilp

(74) Agent and/or Address for Service
A A Thornton & Co
Northumberland House, 303-306 High Holborn, LONDON, WC1V 7LE, United Kingdom

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(54) Abstract Title
Anisotropic plasma etching of a silicon wafer with aperture between plasma source and wafer

(57) The anisotropic etching of a silicon wafer 9 by means of a plasma source 8 and a reactive gas or gas mixture (eg fluorine) includes an aperture 15 with an active surface for electron/ion recombination between the plasma source and the wafer. The aperture is in the form of a perforated diaphragm 14 with the active surface comprising a vertical cylindrical screen 16 of aluminium. An absorber 17 (eg silicon or graphite) for reactive particles surrounds the wafer.

Fig. 2

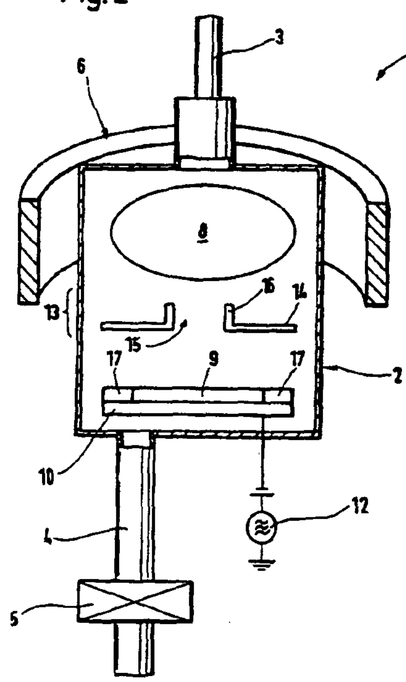

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Fig. 1

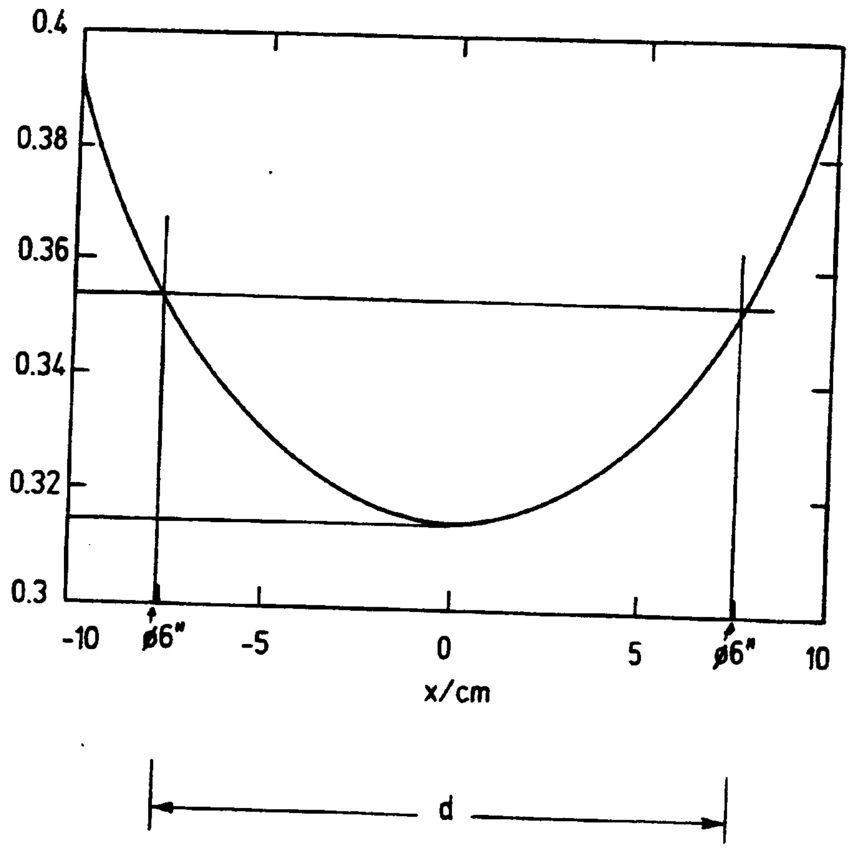


Fig. 2

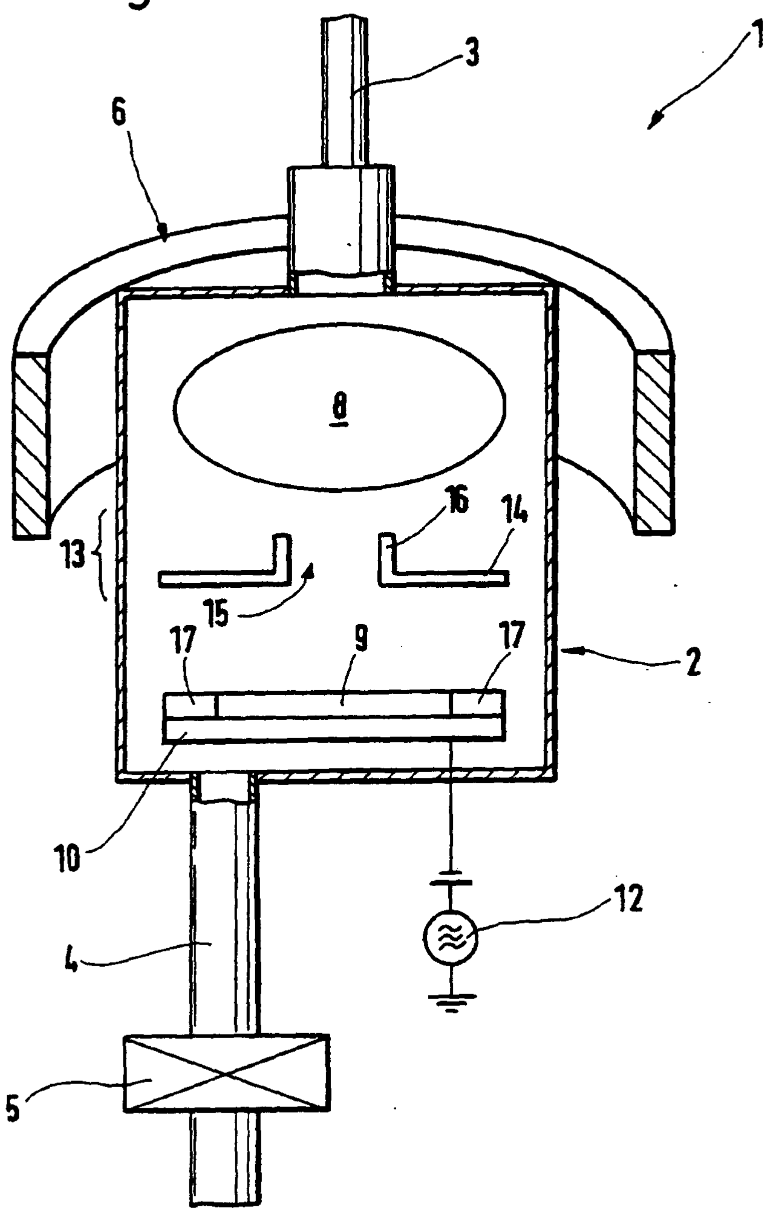


Fig. 3

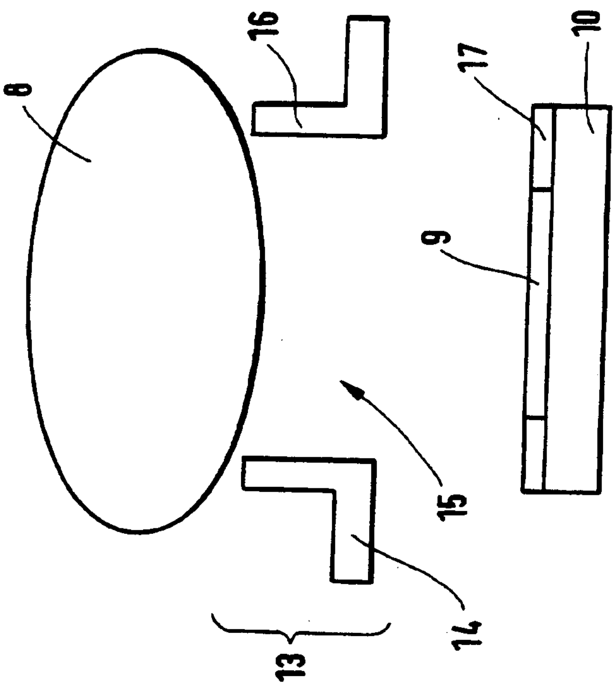
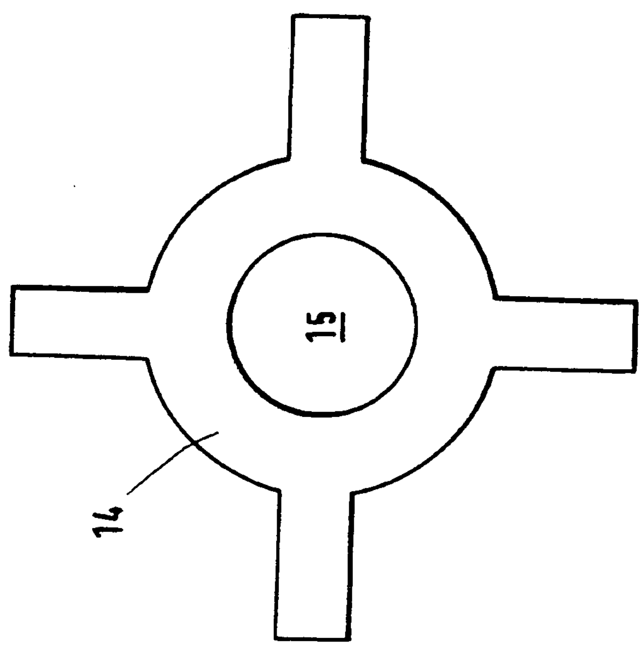


Fig. 4



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<u>Process and device for the anisotropic etching of substrates</u>

Prior art

The invention relates to a process and a device for the anisotropic etching of substrates by means of a plasma.

The etching of substrates by means of a plasma is known. It is used, above all, in the case of substrates made of silicon for semiconductor technology, particularly in the manufacture of chips made of silicon wafers. In the latter process, defined structures, such as indentations for example, are etched into the substrate through etching masks. The etching masks in question are masking layers, for example layers of photosensitive resist, applied to the surface of the substrates. The plasma is ignited by the excitation of reactive gases or gas mixtures by means of high-frequency electromagnetic radiation. For this purpose use is made, for example, of an inductively coupled plasma source (ICP = inductive coupled plasma) with high-frequency excitation. A typical ICP source has an exciting coil with one or more windings, which is placed around the plasma volume and has a high-frequency current, for example one with a frequency of 13.56 MHz, flowing through it for the purpose of exciting the plasma. One end of the coil (the so-called "hot" end) is accordingly connected to a high-frequency source.

A generic etching process for the deep etching of silicon with an ICP source is known from DE 42 41 045 C1.

However, the alternating field or magnetic field of the exciting coil is inhomogeneous. This inhomogeneity brings about an increase in the quantity of ions and reactive particles at the edge of the plasma compared with the

middle. Because of this excitation geometry, different etching rates are observed in the centre and at the edge of the substrate. In the middle of a wafer with a diameter of 150 mm, for example, the etching rate may be up to 20% lower than at the edge region of the substrate.

Furthermore, the stray electrical fields emanating from the "hot" end of the coil, the end which is carrying high voltage, lead to a correspondingly strong deformation of the inductive plasma. At the same time, the plasma is displaced from the centre of the exciting coil towards the "hot" end of the coil. Accordingly, the erosion of the etching mask is very uneven and is displaced from the centre of the substrate towards the edge region. In the region of the substrate which is adjacent to that end of the exciting coil in the plasma source which is carrying high voltage, the erosion is lower than in those regions of the substrate which are more remote from the "hot" end of the coil. These inhomogeneities result in inaccuracies in the structures etched in.

Advantages of the invention

The process according to the invention having the features indicated in claim 1 and the device according to the invention having the features indicated in claim 10 have the advantage that the inhomogeneities described are compensated for to a considerable extent. The inhomogeneity of the etching rate can be at least halved by the incorporation and optimisation of an aperture according to the invention. At the same time, irregular erosion of the etching mask is almost completely suppressed. Under these circumstances, it is even possible to observe slight overcompensation, that is to say the erosion of the etching mask decreases slightly towards the edge of the substrate.

The mask profile is now centred. The reason this effect is particularly advantageous is that it makes it possible to apply the photosensitive resist in smaller layer thicknesses. This is accompanied by greater accuracy of structuring and a diminution in the structural breadths that can be manufactured.

The process and device according to the invention are based on the knowledge that the abovedescribed inhomogeneities of the plasma are kept away from the substrate by the process and device according to the invention. The aperture according to the invention offers an enlargement of the area which is active in respect of electron/ion recombination, while the acceptance angle is lessened towards the substrate. As a result of expansion of the plasma underneath the aperture towards the substrate, there occurs a thinning of the reactive particles, that is to say both of the ions and also of the free radicals, which becomes active particularly in the edge region of the substrate.

The inhomogeneity of the high-frequency coil field of the exciting coil and the influence on the plasma of the electrical fields emanating from the end of the coil carrying high voltage are therefore screened towards the substrate. Compensation is based on electron/ion recombination at the walls of the aperture, as a result of which the ionic current density in the edge region of the substrate decreases, and on a thinning effect which likewise becomes active in the edge region of the substrate.

The present invention therefore brings about an improvement in the uniformity of an ICP source towards the substrate.

As a result of the measures mentioned in the subclaims, advantageous further developments of, and improvements to, the process mentioned in claim 1 or the device mentioned in claim 10 are possible.

A preferred form of embodiment of the aperture according to the invention consists in a perforated diaphragm with an approximately cylindrical tube which is placed thereon and is introduced into the plasma. The cylindrical tube offers an enlargement of the area which is active in respect of electron/ion recombination over a prolonged distance of travel of the electrons or ions in the volume enclosed by the said recombination area.

By charging the substrate electrode with an absorber, around the edge of the substrate, which is made of a material that consumes the particular reactive particles, it is additionally possible to simulate a substrate charge which extends over the edge region of the substrate and consumes reactive particles. It is thereby possible to compensate for a further cause of the uneven erosion of the etching mask. In the edge region of the substrate, fewer reactive particles are absorbed by the substrate itself than in the middle. At the same time, reinforcedly reactive particles are produced at the edge because of the inhomogeneity of the plasma. The concentration of the reactive particles is therefore increased in the edge region of the substrate. The intercepting shield absorbs this excess. It is possible, depending upon the dimensions of the intercepting shield, to achieve absolutely homogeneous etching over the area of the substrate or even to invert the etching rate distribution over the area of the substrate (the etching rate decreases towards the edge).

Drawings

The invention will be explained in greater detail below with the aid of an exemplified embodiment with reference to the drawings, in which:

figure 1 shows the magnetic field distribution of an inductively coupled plasma source with a single coil winding;

figure 2 shows a diagrammatic representation of a plasma-processing installation with an exemplified embodiment of a device according to the invention;

figure 3 shows a diagrammatic detail view of the aperture in figure 2;

figure 4 shows a diagrammatic plan view of the perforated diaphragm in figure 3.

Figure 1 shows the calculated amplitude characteristic of the field distribution of the magnetic field of a typical ICP exciting coil. The coil in question is one which has a high-frequency current flowing through it, a diameter of 40 cm and a single winding. This coil is contained in a commercial plasma source for generating a high-frequency magnetic field for the inductive excitation of plasma. This field distribution essentially corresponds to the plasma density distribution of the plasma excited thereby. "Plasma density distribution" is understood to mean the distribution of the ion density and of the density of reactive species, such as radicals for example.

In this characteristic curve, the diameter d of a silicon wafer with a diameter of 150 mm (6" wafer) is plotted, the field minimum being located in the middle point of the wafer. This centrosymmetry corresponds to the case of electrical interference fields which are not present. Without interference fields of an electrical kind, therefore, the plasma density distribution is also centrosymmetrical.

It is perceived that the plasma density thus calculated increases by more than 12% from the middle to the edge of the 6" silicon wafer. Since the acceleration of the ions in the direction of the substrate leads, because of the substrate bias voltage, to an essentially equal ionic current density, the etching rate at the edge of the silicon wafer is considerably higher than in the middle.

Figure 2 shows diagrammatically a plasma-processing installation 1, in which a device 13 according to the invention is used. The plasma-processing installation 1 has a reactor 2 into which a reactive gas which, in the exemplified embodiment, is a fluorine-supplying one, or a fluorine-supplying gas mixture can be conducted via an infeed connection piece 3. The desired pressure can be set in the reactor 2 via an extractor connection piece 4 with a regulating valve 5.

A high-voltage plasma source with an ICP coil 6 for generating a high-density plasma 8 is also provided. The coupling-in of the high-frequency magnetic field produced by the coil 6 into the reactor 2 charged with reactive gas leads to the ignition of the plasma 8. The substrate 9, in this case a 6" silicon wafer, is located on the substrate electrode 10 which is connected to a further high-frequency voltage source.

In the exemplified embodiment, the aperture 13 according to the invention, which aperture is diagrammatically represented in figures 3 and 4, is inserted between the inductive plasma source and the substrate 9 for the purpose of homogenising the plasma density distribution or the ionic current density. The aperture 13 serves to diaphragm out the intensive edge fractions of the plasma and, at the same time, to keep stray electrical fields away from the substrate 9. The aperture 13 has a perforated diaphragm 14 which can be produced, for example, from 15 mm thick aluminium. Figure 4 shows the diaphragm geometry. The perforated diaphragm 13 is fastened in the device 1, for example, with the aid of a flanged part (not represented). The diameter of the opening 15 in the perforated diaphragm 14 is greater than the diameter d of the wafer 9. In the exemplified embodiment, the diaphragm size was 170 mm for a diameter of the wafer 9 of 150 mm (6" wafer).

In order to complete the device 13 according to the invention, a screen 16 in the form of a vertical cylinder made, for example, of aluminium with a wall thickness of 10 mm, was inserted in the installation 1. The cylinder 16 may be fixed to the edge of the perforated diaphragm 14, but may also be fastened separately. Cylinders 13 with heights of 70 mm, 49 mm and 25 mm were tried.

Also installed on the substrate electrode 10 was an absorber 17, which is coupled to the said substrate electrode in a thermally satisfactory manner (for example with vacuum grease). The material of the absorber 17 is so chosen that the particular reactive particles are absorbed and thereby consumed. In the present case, silicon or graphite (carbon) can be used for the absorption of fluorine. For other reactive particles, quartz glass or plastics may also be suitable.

A cylinder height of 25 mm proved to be optimum, both in respect of the uniformity of the etching rate and also for the erosion of the silicon or etching mask. Higher cylinders led to a distinct decrease in the etching mask erosion towards the edge of the wafer, so that the ionic current density in the edge region of the wafer was reduced to too great an extent (overcompensation).

As a check test, the cylinder 16 was removed and ordinary perforated diaphragms 14 with different diameters were tried. The diameters used were 70 mm, 110 mm, 130 mm, 150 mm and 170 mm.

In the case of the diaphragm diameters of up to 150 mm, which were smaller than the substrate diameters, the etching profiles displayed an intolerable tilt out of the vertical in the direction of the interior of the diaphragm, that is to say the etched troughs were etched into the substrate obliquely - at an angle ≠ 90°. It was possible, by enlarging the diaphragm opening, to diminish this harmful effect until it disappeared completely at a diaphragm opening which exceeded the substrate diameter. However, with a diaphragm opening of this kind of, in the exemplified embodiment, 170 mm, it was almost impossible to reduce the etching rate at the edge of the wafer any further. The perforated diaphragm 14 was therefore inactive for this diameter.

An additional area for electron/ion recombination, the cylinder 16 in the exemplified embodiment, is therefore necessary, which makes possible an improvement in the uniformity of the plasma without the effect of profile-tilting in the edge region of the substrate 9. Even a diaphragm diameter which is greater than the substrate diameter thereby brings about an improvement in the

uniformity of the plasma acting on the substrate 9, without impairing the profile shapes.

With the diaphragm device according to the invention, the etching rate distribution can be improved, depending on the nature and size of the substrate and of the plasma source, by at least a factor of 2 for all trench widths. In trials with a representative type of test wafer with and without an aperture 13, the etching rate distributions listed in the following tables are obtained.

In all the trials, 6" silicon wafers were etched for 10 mins. In all cases, the etching mask made of photoresist had a thickness of 1.1 µm at the beginning of the treatment. In these trials, a quartz intercepting shield was placed around the wafer. Therefore, no absorption of fluorine radicals took place in the edge region of the wafer. All that is observed in these trials is the effect of the aperture according to the invention. The deviation was calculated from the difference between the maximum and minimum etching depths, divided by the mean etching depth. This corresponds to approximately twice the quotient from the difference between the maximum and minimum etching depths and the sum of the maximum and minimum etching depths:

$$\%\ \text{deviation} = \frac{(\text{max. etching depth} - \text{min. etching depth}) \cdot 100\%}{\text{mean etching depth}}$$

$$\%\ \text{deviation} \quad 2 \cdot \frac{\text{Max.} - \text{Min.}}{\text{Max.} + \text{Min.}}$$

Table 1

Etching without aperture

Trench width	Erosion middle of wafer	Max. erosion edge of wafer	Deviation
2.2 µm	15.1 µm	17.3 µm	14 %
5.0 µm	17.5 µm	20.2 µm	15 %
60 µm	23.2 µm	27.0 µm	16 %

Table 2

Etching with aperture, perforated diaphragm diam. 170 mm, cylinder height 25 mm

Trench width	Erosion middle of wafer	Max. erosion edge of wafer	Deviation
2.2 µm	17.4 µm	18.7 µm	7.4 %
5.0 µm	19.6 µm	21.3 µm	8.7 %
60 µm	25.4 µm	27.0 µm	6.3 %

A distinct improvement in the uniformity of the etching rate by about a factor of 2 is perceived, namely the same for all the trench widths investigated. The profiles in the trenches 60 µm broad are exactly perpendicular under the process parameters chosen, with a tendency towards being slightly positive in the narrow trenches, that is to say the trench troughs narrow minimally towards the bottom. Profile-tilting out of the vertical can no longer be perceived. Naturally, the desired profile shape can be influenced in one or other direction by varying the parameters.

At the same time, it is observed that the erosion of the photoresist of the etching mask is very much more uniform. Whereas, without the aperture 13, there is a factor of 2 (70% referred to the mean resist erosion) between the minimum erosion rate in the centre of the "eye", which is

displaced from the middle of the wafer by 4 cm, and the maximum erosion rate at the opposite edge of the wafer, the erosion rate with the aperture 13 deviates 17.5% at most, and on average even distinctly less, the resist profile being exactly centred towards the middle of the wafer. The thickness of the residual resist grows, while the resist erosion has a tendency to decline slightly towards the edge of the wafer.

Since the resist erosion mechanism is a purely ion-induced etching operation, the residual resist profile is a direct measure of the distribution of the ionic current density towards the substrate surface. The slight rise in the residual resist thickness towards the edge region of the substrate thus means a complete compensation, or even a slight overcompensation, for the inhomogeneity of the ionic density distribution which is occasioned by the source.

The effect of the centring and better uniformity is that the selectivity of the process vis-à-vis the etching mask can be better utilized over the entire surface of the substrate. In addition, the accuracy of the trenched structures is dramatically improved over the surface of the substrate. Since the structural loss resulting from the loss of resist is about equally large all over, this effect benefits the chip yield.

The process and device according to the invention are therefore capable of almost completely screening electrostatically coupled-in stray fields from the region of that end of the coil which carries high voltages, towards the substrate, and of additionally homogenising the ionic current density.

In a second series of trials, the effect of the absorber 17 was investigated in addition to the aperture used. In the exemplified embodiment, the absorber 17 consisted of silicon. However graphite, for example, is also suitable for absorbing reactive fluorine particles. The process parameters were the same as described above. The decline in the etching rate at the edge of the wafer in dependence on the breadth of the absorber 17 was investigated first.

Table 3

Edge-middle etching rate difference in dependence on the breadth of the absorber 17.

Trench width	breadth 5 cm	breadth 2.5 cm	breadth 1 cm
2.2 µm	- 16.8 %	- 11.5 %	- 3.6 %
5.0 µm	- 15.7 %	- 10.8 %	- 4.4 %
60 µm	- 20.8 %	- 13.8 %	- 6.7 %

This effect of a decrease in the etching rate towards the edge of the wafer is attributable to the fact that, without an active absorber 17 in the middle of the wafer, more reactive particles, fluorine radicals in the exemplified embodiment, are consumed than in the edge region of the wafer. With an active absorber 17 made of silicon or graphite, the concentration of fluorine radicals in the edge region is lowered, since the absorber 17 absorbs a certain fraction and consumes them in etching reactions. The etching rate on the wafer 9 therefore decreases.

Naturally the use of other materials, such as polymers for example, which intercept reactive particles is conceivable.

Claims

1. Process for the anisotropic etching of a substrate by means of a plasma, wherein a high-frequency electromagnetic alternating field is generated by means of an inductively coupled plasma source and a reactive gas or reactive gas mixture is exposed to the said high-frequency electromagnetic alternating field for the purpose of producing the plasma, and wherein the electrically charged particles of the plasma are accelerated in the direction of the substrate and an aperture constructed as a perforated diaphragm is disposed between the plasma source and the substrate, **characterised in that** there is associated with the aperture at least one active surface for electron/ion recombination, the active surface being constructed as an approximately cylindrical top-piece on the aperture and the diameter of the aperture being greater than the diameter of the substrate.

2. Process according to claim 1, characterised in that a perforated diaphragm is used as the aperture, and an approximately cylindrical top-piece as the active surface.

3. Process according to claim 1 or 2, characterised in that an aperture or perforated diaphragm and/or a top-piece made of metal is/are used.

4. Process according to claim 3, characterised in that a fluorine-resistant metal is used.

5. Process according to claim 4, characterised in that aluminium is used as the fluorine-resistant metal.

6. Process according to one of the preceding claims, characterised in that the density of the reactive particles of the plasma is diminished in the edge region of the substrate.

7. Process according to claim 6, characterised in that an absorber which consumes the reactive particles is placed around the substrate.

8. Process according to claim 5, characterised in that an absorber made of quartz, silicon, plastic and/or graphite is used.

9. Process according to one of the preceding claims, characterised in that ions and/or radicals of fluorine and/or fluorine compounds are used as the reactive particles.

10. Device (13) for homogenising a plasma produced by an inductively coupled plasma source, characterised in that it has an aperture (14) with at least one additional active surface (16) for electron/ion recombination.

11. Device according to claim 10, characterised in that the aperture (13) has a perforated diaphragm (14) and an approximately cylindrical top-piece (16).

12. Device according to claim 10 or 11, characterised in that the perforated diaphragm (14) and/or the top-piece (16) consist of metal.

13. Device according to claim 12, characterised in that the metal is fluorine-resistant.

14. Device according to claim 12 or 13, characterised in that the metal is aluminium.

15. Plasma-processing installation (1) for the anisotropic etching of a substrate (9) by means of a plasma (8), the said installation having a plasma source for generating a high-frequency electromagnetic alternating field, a reactor (2) for producing a plasma (8) from reactive particles by the action of the high-frequency electromagnetic alternating field on a reactive gas or reactive gas mixture, and a substrate electrode (10) for accelerating the ionic current contained in the plasma (8) in the direction of the substrate (9), characterised in that the plasma-processing installation (1) has an aperture (13) according to at least one of claims 10 to 14 between the plasma source and the substrate electrode (10).

16. Plasma-processing installation according to claim 15, characterised in that the diameter of the aperture (13) is greater than the diameter of the substrate (9).

17. Plasma-processing installation according to claim 15 or 16, characterised in that it has an absorber (17) for reactive particles of the plasma (8), which absorber is disposed around the substrate (9).

18. Installation according to claim 17, characterised in that the absorber (17) consists of silicon, quartz, plastic and/or graphite.

19. Process for the anisotropic etching of a substrate by means of a plasma, substantially as herein before described with reference to the accompanying drawings.

20. Device for homogenising a plasma substantially as hereinbefore described with reference to the accompanying drawings.

21. Plasma-processing installation substantially as hereinbefore described with reference to the accompanying drawings.

The Patent Office

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Claims searched: 1-21

Examiner: Graham Russell
Date of search: 21 October 1998

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Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.P): B6J (JMX, JMY); H1K (KLEXA)

Int Cl (Ed.6): H01L 21/3065

Other: Online: EPODOC

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
A	EP 0065085 A2	(IBM) see page 3 lines 31-34	7,8,17,18
X	EP 0047395 A2	(IBM) see page 3 line 17 - page 4 line 4 & page 11 line 16 - page 12 line 28	10,15

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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